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Behavioral responses of sea turtles to lightsticks used in longline fisheries

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Abstract

Sea turtles are sometimes inadvertently captured by pelagic longline fisheries. As a consequence, some drown or suffer injuries, and longline bycatch has been identified as one factor contributing to the decline of marine turtle populations. Understanding what stimuli attract turtles to longlines will therefore be useful in efforts to reduce the number of turtles that become hooked or entangled. Lightsticks, which are often placed on longlines to attract tuna (*Thunnus* sp.) and swordfish *Xiphus gladius*, may also attract sea turtles. To investigate this possibility, we conducted laboratory experiments with captive-reared juvenile loggerheads *Caretta caretta* and wild-caught post-hatchling loggerheads to study their responses to these lights. Both age classes oriented toward glowing lightsticks, suggesting that such lights may play a role in attracting turtles into the vicinity of longlines.

Introduction

Over the past two decades, many sea turtle populations have declined significantly. In particular, nesting populations of leatherback *Dermochelys coriacea* and loggerhead *Caretta caretta* turtles in the Pacific Ocean have dramatically decreased (Crowder, 2000; Spotila *et al*., 2000; Kamezaki *et al*., 2003; Limpus & Limpus, 2003). Turtle bycatch associated with pelagic longline fisheries has been implicated as one factor contributing to this decline in at least some populations (Spotila *et al*., 2000; Lewison, Freeman & Crowder, 2004).

Pelagic longline fishing involves a single main fishing line that can stretch over 50 km with thousands of individually hooked lines branching off from the main line (Boggs & Ito, 1993; Ito, Dollar & Kawamoto, 1998; Bigelow *et al*., 2006). This fishing method is used in every ocean basin and commonly targets tunas (*Thunnus* spp.), swordfish *Xiphus gladius* and dolphin fish (*Coryphaena* spp.) (Boggs & Ito, 1993; Ito *et al*., 1998; Bartram & Kaneko, 2005). In addition to these targeted fish, longline fisheries also inadvertently catch sea turtles (Yeung, 1999, 2001; Garrison & Richards, 2004; Lewison *et al*., 2004).

Loggerhead and leatherback turtles are the species that commonly come in contact with longlines (Lewison *et al*., 2004). Turtles are often hooked in the mouth, throat or digestive tract and subsequently drown when they are unable to surface to breathe (Yeung, 1999, 2001; NMFS-SEFSC, 2001; Garrison & Richards, 2004). Turtles are also sometimes hooked in their flippers and carapaces, or become entangled in the lines (Yeung, 1999, 2001; NMFS-SEFSC, 2001; Garrison & Richards, 2004). Estimates of sea turtle bycatch suggest that, in the year 2000 alone, pelagic longlines caught over 200 000 loggerheads and 50 000 leatherbacks (Lewison *et al*., 2004).

Strategies to diminish the impact of longline fisheries on sea turtle populations have included seasonal and area fishing closures, attempts to decrease the mortality of captured turtles through better handling practices, alteration of fishing methods and changes in gear (Swimmer *et al*., 2005; Watson *et al*., 2005; reviewed by Gilman *et al*., 2006). In the North Atlantic swordfish fisheries, a reduction of sea turtle bycatch was achieved by using 18/0 circle hooks and mackerel *Scomber scombrus* bait (Watson *et al*., 2005). It is uncertain, however, whether these methods will be equally efficacious in other longline fisheries (Gilman *et al*., 2006).

An understanding of the sensory stimuli that attract turtles into the vicinity of longline sets may be useful in developing additional gear modifications that will reduce turtle bycatch (Swimmer *et al*., 2005; Gilman *et al*., 2006). A common practice in some longline fisheries is to attach glowing lightsticks to the branch lines in order to attract fish into the vicinity of the baited hooks (Ito *et al*., 1998; Witzell, 1999; Bigelow *et al*., 2006). Lights used include chemiluminescent lightsticks and battery-powered light-emitting diodes (LEDs). As a first step toward determining whether these lights also attract sea turtles, we conducted laboratory studies in which we investigated the responses of loggerhead turtles to these lights.

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Methods

Experiments with captive-raised juvenile loggerhead sea turtles

Animals

Loggerhead turtles captured in pelagic longline fisheries have straight carapace lengths (SCLs) that typically range from 40 to 65 cm (Bolten, 2003; Watson *et al*., 2005). To match this size class, we used juvenile turtles that measured 42–52 cm SCL and were *c*. 2.5 years old. These loggerheads were raised in captivity at the NOAA Fisheries Service Sea Turtle Facility in Galveston, TX, USA, using husbandry protocols of the NOAA Fisheries Service (Higgins, 2003).

Experimental setup and protocol

Turtles were tested one at a time in a large, fiberglass, circular arena (3.7 m in diameter and 1.5 m deep) filled with *c*. 15 000 L of seawater. The arena was located in a light-proof room. Each turtle was placed in a nylon-Lycra harness that encircled the carapace but did not impede swimming (Avens & Lohmann, 2004). The turtle was then tethered (using a 48 cm length of rope) to a rotatable lever-arm (48 cm in length) that was connected to an electronic tracking unit (Lohmann, 1991; Light, Salmon & Lohmann, 1993; Avens & Lohmann, 2004; Lohmann *et al*., 2004). The tracking unit was placed over the center of the tank using a wooden crossbar and was wired to a computer in an adjacent room (Fig. 1). Tracking software enabled us to record continuously the turtle's swimming direction. To observe the swimming behavior of the turtle, an infrared video camera and an infrared light were mounted directly above the arena. To ensure that the room remained dark during experiments, the video was displayed on a monitor in an adjacent building.

We tested the responses of juvenile loggerhead turtles to green, blue, yellow or inactive (control) Duralume® (Lindgren Pitman Inc., FL, USA), chemical lightsticks, each measuring 10.2 cm in length. In addition, one group of turtles was exposed to an orange Electrolume® (Lindgren Pitman Inc., FL, USA), a battery-powered lightstick consisting of LEDs. The lightsticks were provided by Lindgren-Pittman Inc. (Lindgren Pitman Inc., FL, USA), a manufacturer of longline fishing gear.

Experiments were conducted at night. Before each trial, a lightstick was suspended 50 cm below the water's surface with a monofilament fishing line. To ensure that turtles did not orient to some feature of the room or setup other than the lightstick, the position of the lightstick in the testing arena was alternated between north and south in successive trials. For purposes of analysis, data were normalized so that the position of the lightstick was considered to be 0° for each trial.

To begin each experiment, a turtle was taken from its holding tank and carried to the testing arena in a plastic container. It was then harnessed and tethered to the lever-arm. After a 5-min acclimation period, the tracking software was activated and the computer recorded the turtle's orientation every 10 s for the next 10 min.

Preliminary experiments revealed that not all turtles were active when introduced to the arena; some floated motionless rather than swimming, ceased swimming after a few minutes, or stopped intermittently for long intervals. In addition, tests using the same individual on different nights revealed that turtles that failed to swim on the first night sometimes swam on the second or vice versa, and that the direction of swimming sometimes also varied among nights. For these reasons, the experimental design involved exposing each turtle to the same kind of lightstick on each of

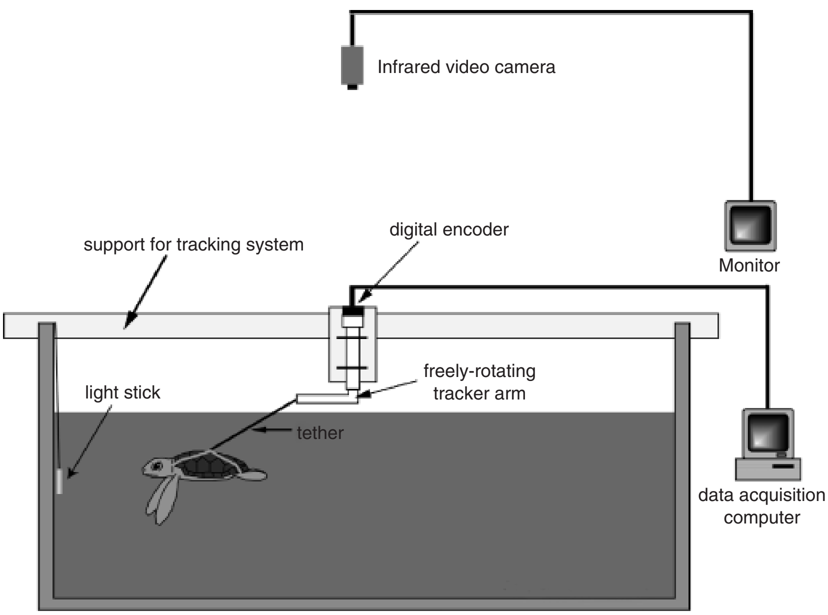

Figure 1 Diagrammatic representation of the orientation arena and the data acquisition system used to monitor the orientation of juvenile and post-hatchling sea turtles. The dimensions of the arenas and tracking systems used for juvenile and post-hatchling turtles differed; see text for details.

several different nights, and then calculating an average response using standard procedures for circular statistics (Batschelet, 1981; see below).

Because turtles sometimes floated motionless instead of swimming, a stopwatch was used in each trial to determine how much time the turtle remained inactive. If a turtle failed to swim for more than 25% of the 10-min trial, the trial was terminated. The turtle was then removed from the arena and tested again with an identical lightstick on subsequent nights until three successful trials had been completed, or until five such trials had been attempted. Data from turtles that failed to complete three trials successfully (36% of turtles tested) were not included in our analysis. No turtle was tested more than once on any given night, regardless of whether the trial was successful or not.

In accordance with standard procedures for circular statistics (Batschelet, 1981; Zar, 1999), the three nightly mean angles for each turtle were used to calculate a single mean angle and r-value for that individual. Data for groups of turtles exposed to each type of lightstick were then analyzed using the Hotelling test (Batschelet, 1981).

Experiments with post-hatchling turtles

We also studied the responses of post-hatchling loggerheads to lightsticks. Post-hatchlings were collected from floating *Sargassum* seaweed patches in the vicinity of the Gulf Stream off the coast of Cape Canaveral, FL, USA. The turtles were captured using dip-nets and had SCLs ranging from 44 to 50 mm. The turtles were kept in Styrofoam containers filled with water and transported to Florida Atlantic University where the experiments were conducted.

Testing setup and protocol of indoor experiments

Post-hatchling turtles were tested in a circular arena (1.83 m in diameter) filled with seawater to a depth of 17.8 cm. Each turtle was placed into a nylon-Lycra harness and tethered (using 18.5 cm of monofilament line) to a rotatable lever-arm (18.5 cm in length) that was attached to an electronic tracking unit (Lohmann & Lohmann, 1994). As in the previous experiments, the tracking unit was placed over the center of the circular arena and was wired to a computer that continuously monitored the turtle's swimming direction. An infrared video camera and infrared light mounted directly above the arena allowed one to observe the behavior of turtles on a monitor in a nearby room.

Two groups of turtles were tested at night in a lightproof room. Turtles in the first group (experimental) were harnessed and released in the circular arena with an activated green Snaplight® lightstick (15 cm in length) in either the east or west side of the tank. All turtles were released in the north end of the tank while facing north. After a 5-min adjustment period, the computer program was activated and the orientation of the turtle was recorded every 10 s for the next 10 min. Turtles in the second (control) group were placed in the tank under identical conditions, except that an inactive lightstick was placed in either the east or west side of the arena. Control and experimental trials were alternated, and the position of the lightstick (east or west) was alternated after each pair of trials (i.e. after one control trial and a corresponding experimental trial). For purposes of analysis, data were normalized so that the position of the lightstick was considered to be 0° for each trial.

Whereas the captive-reared juvenile turtles tested previously sometimes failed to swim and had to be tested multiple times (see above), post-hatchling turtles were more active and nearly always swam continuously the first time they were tested. Thus, each post-hatchling was tested only once, and the mean angle for each turtle was calculated on the basis of all data points collected during a single 10-min trial. Data from each treatment group were then analyzed using the Rayleigh test (Batschelet, 1981).

Outdoor experiments

Although the initial experiments with post-hatchlings were conducted in darkness (see above), many longline hooks are set at depths where natural illumination from the sun, moon or stars is visible. To determine whether turtles were attracted to lightsticks under conditions in which at least some ambient light is present, we conducted a second set of experiments under the night sky. The outdoor experiments were carried out in an open courtyard at Florida Atlantic University where cloud cover, lunar phase and the distant glow of city lights resulted in different light levels on different evenings, and where light levels sometimes changed continuously during trials as clouds passed across the sky. The same circular arena, tracking mechanisms, lightsticks and protocol used in the indoor experiment were again used for these outdoor experiments.

Measurement of chemical lightstick and LED emission spectra

An SLM model 8100 spectrofluorometer (SLM Aminco, Urbana, IL, USA) was used to analyze the emission spectra of the chemical lightsticks and battery-powered LEDs. Chemical lightsticks were activated and shaken vigorously to ensure thorough mixing of the chemical reactants. After 5 min, the end of the lightstick was removed and a 10 mL sample of the luminescent contents was pipetted into a cuvette and placed in the spectrofluorometer. To measure the output of the Electrolumes®, the LEDs were removed and wired to 2 AA batteries. The LEDs were placed in the cuvette and inserted into the spectrofluorometer. Spectral measurements for each chemical lightstick and Electrolume® were plotted (Fig. 2).

Results

Juvenile turtle experiments

Juvenile loggerheads tested in the presence of a Duralume® lightstick that had not been activated were not significantly oriented as a group ($n = 13$, $r = 0.17$, NS, Hotelling test;

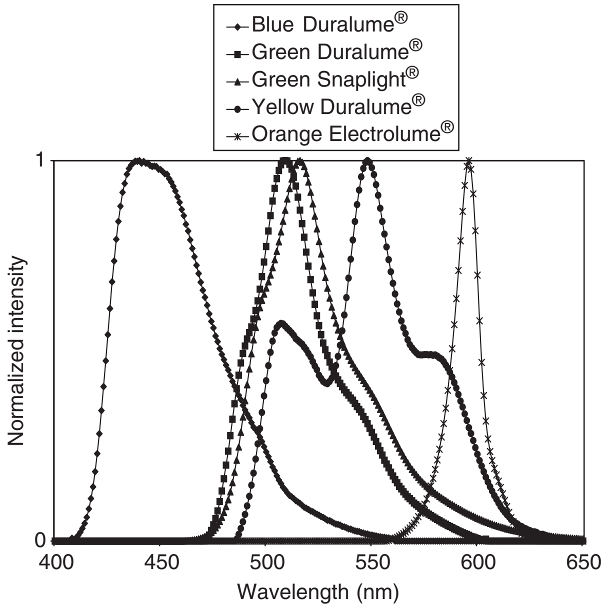

Figure 2 Spectral characteristics of lightsticks used in juvenile loggerhead *Caretta caretta* and post-hatchling experiments.

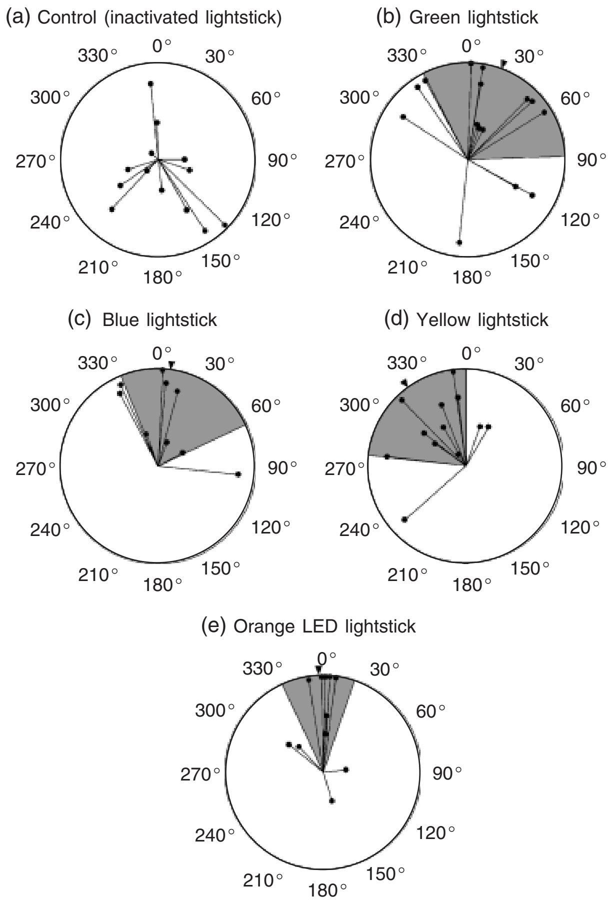

Figure 3 Results from experiments in which juvenile loggerheads *Caretta caretta* were exposed to (a) lightsticks that had not been activated (control trials), (b) glowing green Duralume® lightsticks, (c) blue lightsticks, (d) yellow lightsticks and (e) orange light-emitting diode (LED) lightsticks. Data were normalized so that 0° indicates the position of the lightstick in each trial. The triangle outside the circle represents the mean angle of each group of turtles. Each dot represents the mean swimming direction of a single turtle. The length of the line radiating from the center of the circle is proportional to the mean vector r, with the radius of the circle corresponding to $r=1$. The shaded region of the circle indicates the 95% confidence interval for the mean angle.

Fig. 3a). In contrast, juvenile turtles tested with green lightsticks were significantly oriented as a group with a mean angle of 20.2° [$n = 15$, $r = 0.42$, $P<0.02$, Hotelling test, 95% confidence interval (CI) 333–88°; Fig. 3b]. Turtles were significantly oriented as a group with a mean angle of 7.1° when tested with blue lightsticks ($n = 9$, $r = 0.54$, $P<0.001$, Hotelling test, 95% CI 338–65°; Fig. 3c). Turtles tested in the presence of yellow lightsticks were significantly oriented with a mean angle of 323.9° ($n = 12$, $r = 0.45$, $P<0.001$, Hotelling test, 95% CI 276–0°; Fig. 3d). Also, juvenile turtles were significantly oriented as a group with a mean angle of 358.3° ($n = 11$, $r = 0.55$, $P<0.025$, Hotelling test, 95% CI 335–19°) when tested with orange LED lightsticks (Fig. 3e). The CI of all four experimental treatments overlaps the location of the lightstick (0°).

Post-hatchling experiments

Indoor lightstick experiments

Post-hatchling turtles tested with inactive (control) green Snaplight® lightsticks were not significantly oriented as a group (NS, Rayleigh test; Table 1). In contrast, turtles tested with activated green lightsticks were significantly oriented ($P<0.001$, Rayleigh test, 95% CI ±27°; Table 1).

Outdoor lightstick experiments

Turtles tested under the night sky with inactive lightsticks were significantly oriented as a group ($P<0.05$, Rayleigh test; Table 1). However, the 95% CI (±44°) did not overlap 0°, indicating that the turtles oriented in a direction that was not toward the lightstick. In contrast, turtles tested in the presence of activated green lightsticks oriented significantly toward the lightsticks ($P<0.001$, Rayleigh test, 95% CI ±28°; Table 1).

Discussion

The results indicate that juvenile loggerhead turtles were attracted to glowing green, blue and yellow chemical lightsticks (Figs 3b–e) as well as to orange LED-based Electrolume® lightsticks. In contrast, turtles were not attracted to lightsticks that had not been activated (Fig. 3a). These findings are consistent with the hypothesis that the illumination from lightsticks is an important factor in attracting turtles into the vicinity of longline sets. A caveat, however, is that these experiments were conducted under laboratory

Table 1 Summary of wild-caught post-hatchling responses to green Snaplight® lightsticks

Experiment	n	Mean heading[a]	r-value	Significantly oriented toward the lightstick?
Post-hatchling indoor control (inactive lightstick)	12	257.2°	0.25	No
Post-hatchling indoor green lightstick	12	356.2°	0.77	Yes ($P<0.001$)
Post-hatchling outdoor control (inactive lightstick)	8	150.1°	0.66	No[b]
Post-hatchling outdoor green lightstick	8	344.2°	0.87	Yes ($P<0.001$)

[a]The data were normalized so that the position of the lightstick was at 0°.

[b]Turtles in the post-hatchling outdoor control group were significantly oriented in a direction unrelated to the position of the lightstick. Although the reason for this orientation is not known, a likely explanation is that the ambient night-time illumination produced subtle lighting irregularities around the perimeter of the arena and turtles probably oriented toward these visual cues in the absence of a glowing lightstick. The presence of an activated lightstick overrode this response.

conditions that do not fully reproduce conditions in the ocean. Thus, field experiments are needed to confirm or refute the hypothesis that lightsticks do indeed increase sea turtle bycatch.

Lightsticks are used in some but not all longline fisheries, with usage depending on the species of fish targeted and the particular gear configuration employed on the fishing vessel. In Hawaii, for example, lightsticks are typically used when the target species is swordfish but not when the target is big eye tuna (Bigelow *et al.*, 2006). A common practice when targeting swordfish is to place a lightstick on every other hooked branch line or, alternatively, on every three to five branch lines (Ito *et al.*, 1998). A recent analysis of Hawaiian swordfish longline fisheries revealed that the average longline was 74.5 km long, contained 777 hooked branch lines, used 397 lightsticks and had a mean depth of 64 m (Bigelow *et al.*, 2006). Thus, significant numbers of lightsticks are used in at least some fisheries. Additionally, it appears likely that turtles can detect lightsticks from considerable distances, inasmuch as the intensity of such lights almost certainly exceeds the intensity of bioluminescent flashes, which can be perceived underwater from distances of 45–90 m (Widder, 2002).

If lightsticks do indeed attract sea turtles into the vicinity of longlines, then a possible strategy for reducing turtle bycatch is to develop lightsticks that are less attractive to turtles. Potential modifications might include placing shades on the lightsticks, making the lights blink or using lightsticks that generate certain, specific wavelengths that might repel turtles (Wang *et al.*, 2006). Interestingly, hatchling loggerheads that have just emerged from their nests have an aversion to light with a narrow band of wavelengths between 560 and 600 nm, provided that the light is presented to the turtles while they are on land (Witherington & Bjorndal, 1991). Whether this aversion persists after turtles enter the ocean, or after they mature to the size and age at which they encounter longlines, is not known.

In our experiments, loggerhead turtles were attracted to yellow chemical lightsticks (Fig. 3d) and to battery-powered orange LED lightsticks (Fig. 3e). Spectral analyses, however, revealed that the yellow chemical lightsticks produced a broad range of light with a primary peak at 548 nm and two secondary peaks at 510 and 570 nm (Fig. 2). Thus, much of the light was outside the 560–600 nm range that hatchlings avoid while crawling on the beach (Witherington & Bjorndal, 1991). The orange LED lightstick produced a narrower range of wavelengths centered at 595 nm (Fig. 2), but much of the light still consisted of wavelengths greater than 600 nm. Further experiments with lightsticks that produce light only within the 560–600 nm range are needed to determine whether juvenile loggerheads retain an aversion to light in the green-yellow to yellow-orange range. Regardless, our results indicate that juvenile turtles are attracted to the yellow chemical lightsticks and orange LED lightsticks that are presently used in longline fisheries.

Experiments with post-hatchling loggerhead turtles captured in or near the Gulf Stream indicated that these turtles also were attracted to lightsticks (Table 1). Although these turtles were significantly smaller than those that normally encounter longlines, the results suggest that turtles spanning a range of ages and sizes are attracted to lightsticks and that the attraction is not unique to captive-reared turtles. The outdoor experiments with post-hatchlings indicated that turtles were attracted to activated lightsticks not only in complete darkness but also under outdoor night conditions (Table 1). Given that the south Florida night sky is somewhat brighter than a natural night sky due to urban lighting, these results suggest that loggerhead turtles are attracted to lightsticks under a range of lighting conditions that probably bracket those typical of longline sets at night.

Longlines that target swordfish are typically set at dusk and soaked overnight. Although many sea turtles are captured or entangled by longlines during the night, at least a few data sets suggest that the majority of loggerheads may become hooked during daylight hours. Experiments conducted in the Azores indicate a significant increase in loggerhead capture rates with increased daytime haul-back (Bolten & Bjorndal, 2005). The effect of daylight soak time on loggerhead capture rates, however, was varied and inconclusive in experiments conducted in the western North Atlantic (Watson *et al.*, 2005). Under daylight conditions, lightstick illumination is likely to be less conspicuous than during the night, but might still function in attracting turtles under conditions in which ambient illumination is decreased by depth, water turbidity, clouds or time of day. Detailed underwater measurements will be needed to determine exactly how the visibility of lightsticks is affected by normal changes in lighting that occur over the day–night cycle.

Regardless of these considerations, our experiments provide the first direct evidence that lightsticks used in longline fisheries attract sea turtles. The results also indicate the need for carefully controlled field studies to determine whether lightsticks do indeed increase turtle bycatch. In addition, the methodology developed in this study may be useful in testing whether other species of turtles (e.g. leatherback turtles) are also attracted to lightsticks and may be useful for testing the efficacy of modified lightsticks designed to be less attractive to sea turtles.

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